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The El Niño/Southern Oscillation and Precipitation Variability in Baja California, Mexico

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RESUMEN

Este trabajo analiza la variabilidad de la precipitación en Baja California en relación con los eventos El Niño/Oscilación del Sur (ENOS), utilizando el Indice de Oscilación del Sur (IOS). Para evaluar los patrones de precipitación se analizaron los datos de 102 estaciones pluviométricas. Se tomaron promedios directos de los datos de las estaciones con registros de más de 30 años, pero los datos de estaciones con registros más cortos fueron normalizados. Para probar la uniformidad de las anomalías de precipitación se comparó el IOS con la media de anomalías de precipitación para las estaciones de largo plazo (establecidas antes de 1960), en ocho subregiones de Baja California. Los resultados mostraron que, en contraste con California, la variabilidad interanual de la precipitación, tanto anual como mensual, está fuertemente ligada al IOS. Durante los eventos El Niño la precipitación es por arriba de lo normal, generalmente en febrero y marzo; mientras que en los eventos La Niña las cantidades son subnormales, con las tormentas restringidas generalmente a diciembre y enero. Para años individuales los gradientes de anomalías en precipitación tienden a ser uniformes a lo largo de Baja California. La variabilidad de la precipitación se atribuye a la desviación, causada por ENOS, de la corriente de chorro asociada al frente polar sobre la costa del Pacífico, lo cual está descrito en otros estudios. En los eventos El Niño la circulación adquiere un patrón positivo de tipo Pacífico-Norteamérica (PN), con intensificación de la teleconección Hemisferio Norte-Tropical, expresado en una desviación sureña de la corriente de chorro a través de Baja California. Hay una fuerte advección debido a vientos húmedos del oeste sobre la costa occidental de Norteamérica. En los eventos La Niña la circulación compuesta adquiere un patrón PN negativo, y la corriente de chorro se encuentra al norte de Baja California y California. Esto produce una débil advección de los vientos húmedos del oeste. Los cambios estacionales en las anomalías de precipitación se pueden relacionar con los desplazamientos geográficos en el forzamiento diabático desde la alberca ecuatorial de agua caliente y las consecuentes teleconnecciones sobre el tren extratropical de ondas en la región Pacífico-Norteamérica. La uniformidad anual en las anomalías de precipitación sobre las ocho subregiones de Baja California sugiere que las tormentas frontales no producen gradientes orográficos anómalos de precipitación durante los eventos El Niño. Los pronósticos oportunos de largo plazo pudieran ayudar a que el uso del suelo en esta región sea congruente con el patrón cíclico de sequías seguidas por inundaciones.

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ABSTRACT

This study evaluates precipitation variability in Baja California in relation to the El Niño/Southern Oscillation (ENSO) using the Southern Oscillation Index (SOI). To evaluate precipitation climatology, data for 102 weather stations were analyzed. Data were directly averaged for stations with records longer than 30 years, but normalized for stations with shorter records. To test for uniformity of precipitation departures, the SOI was compared with average precipitation departures for long-term stations (established before 1960), in eight subregions of Baja California. The results revealed that, unlike California, the interannual variability of both annual and monthly precipitation is strongly linked to SOI. During El Niño events, above-normal precipitation occurs largely in February and March; but precipitation amounts are subnormal during La Niña events, and mostly limited to December and January. Gradients of precipitation departure tend to be uniform across Baja California during individual years. The variability of precipitation is attributed to the interannual dislocation by ENSO of the polar-front jet stream along the Pacific coast, as described in other studies. In El Niño events, the circulation acquires a positive-phase Pacific-North America (PNA) pattern, with an enhanced Tropical Northern Hemisphere (TNH) teleconnection mode expressed in a southern-branch jet stream across Baja California. There is strong on-shore advection of moist surface westerlies on the West coast of North America. In La Niña events, the composite circulation acquires a negative-phase PNA pattern, and the jet stream is mostly poleward of Baja California and California. This results in weak on-shore advection by moist surface westerlies. Seasonal shifts in precipitation anomalies may be related to geographic shifts in diabatic forcing from the equatorial warm pool, and consequent teleconnections into the extra-tropical wave-train in the Pacific-North American region. The annual uniformity of precipitation departures across the eight subregions of Baja California suggests that frontal storms do not produce anomalous orographic precipitation gradients during El Niños. Timely, long-term precipitation forecasts could help accommodate the region's landuse to its cyclical pattern of drought and flood.

Key Words: Baja California, North America, El Niño/Southern Oscillation, La Niña, Precipitation Variability, Climate, Agricultural and Urban Planning, Landuse, Drought.

1. Introduction

The El Niño/Southern Oscillation (ENSO) comprises the largest source of interannual variability in the troposphere (Diaz and Markgraf, 1992; Lau and Sheu, 1991). The response of precipitation to ENSO reflects complex teleconnections between thermally directed circulation systems of the tropical east Pacific and the polar-front jet stream. The influence of ENSO on precipitation regimes along North America's Pacific coast is under debate. Statistical studies of long-term data for California either support a relationship between precipitation and ENSO (Ramage, 1975; McGuirk, 1982), or find no evidence of such a relationship (Rasmussen and Wallace, 1983; Ropelewski and Halpert, 1986; 1987).

The State of Baja California, the peninsula N of latitude 28 N, lies on the equatorward margin of the planetary jet stream at the transition between the North American mediterranean climatic zone of winter precipitation and summer drought, and desert climates that span the remainder of the peninsula (Wallén, 1955; Hastings and Turner, 1965; Markham, 1972; Pyke, 1972; Cody *et al.*, 1983; Reyes and Rojo, 1985; Reyes Coca *et al.*, 1990). Except for rare tropical cyclones that produce flash floods, warm-season precipitation consists mostly of mountain thundershowers associated with the North American Monsoon (Minnich *et al.*, 1993) which is not hydrologically significant because rains are phased with high evapotranspiration rates.

The interannual variability of precipitation in Baja California, which is linked to ENSO events, strongly affects the reliability of surface and groundwater resources. Long-range forecasts, based on the relationships between ENSO and the distribution of precipitation in Baja California, may help improve the use of water resources, as well as management of natural and agroecosystems in the region. In this study, we evaluate precipitation variability for the winter season in Baja California in relation to the ENSO. We first develop a precipitation climatology of Baja California, related to latitude and frontal orographics during winter cyclones, as a baseline to

evaluate precipitation departures. Secondly, we evaluate whether ENSO produces disparate precipitation responses in relation to latitude and physiography by examining interannual and monthly precipitation departures at two scales of resolution: i) along a latitude gradient from Baja California (Mexico) to northern California (USA) using the interval classification of the SOI, and ii) for eight subregions in Baja California.

2. The study area

The northern half of Baja California is a mountainous region that includes the Sierras Juárez (alt. 1,500-2,000 m) and San Pedro Mártir (alt. 1,800-2,500 m, Fig. 1). Toward the coast is a discontinuous chain of coastal ranges (the "coastal Sierra Juárez", alt. 1,200-1,500 m) that extend from the international boundary to Ensenada Bay. Between these ranges are a series of alluvial valleys from Valle Ojos Negros to Valle Trinidad. At latitude 31°N, the coastal ranges shift eastward to join the Sierra San Pedro Mártir. To the south, the peninsula comprises a series of basins and low ranges (mostly < 1,000 m). Desert plains extend north from the Gulf of California to the Mexicali Valley. The vegetation north of latitude 30° is dominated by chaparral and coastal sage scrub, with mixed conifer and pinyon forests covering the Sierras Juárez and San Pedro Mártir above 1,500 m (Minnich and Franco-Vizcaíno, 1997; 1998). Desert scrub prevails south of latitude 30°, and on desert plains north to the international boundary.

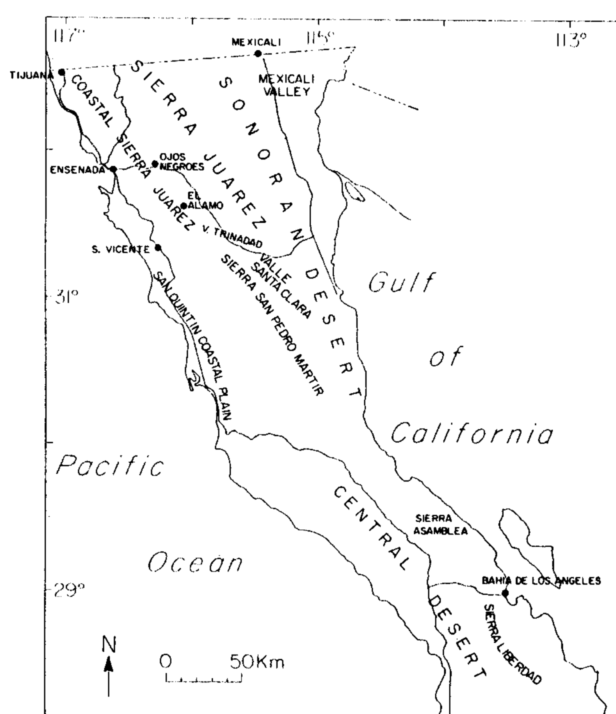


Fig. 1. The State of Baja California with place names given in text.

3. Methods

Previous maps of precipitation in Baja California (e.g. Markham 1972; Pyke 1972) have been evaluated from only 38 stations established from 1948-54, as part of a national program under the Ministry of Agriculture and Water Resources (SARH). An additional 64 stations were established during the 1970's. This expanded database is suitable for developing maps with greater resolution than previous studies. Winter precipitation data for 102 stations (November to May), located in Figure 2, were supplied by the Division Hidrométrica of the former Ministry of Agriculture and Water Resources (SARH) in Ensenada and the Grupo de Meteorología at the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). Precipitation data were subjectively regionalized into ten geographical units based on annual average rainfall and seasonality (Fig. 2). Two regions lacking sufficient stations were consolidated, leaving summary data for eight subregions.

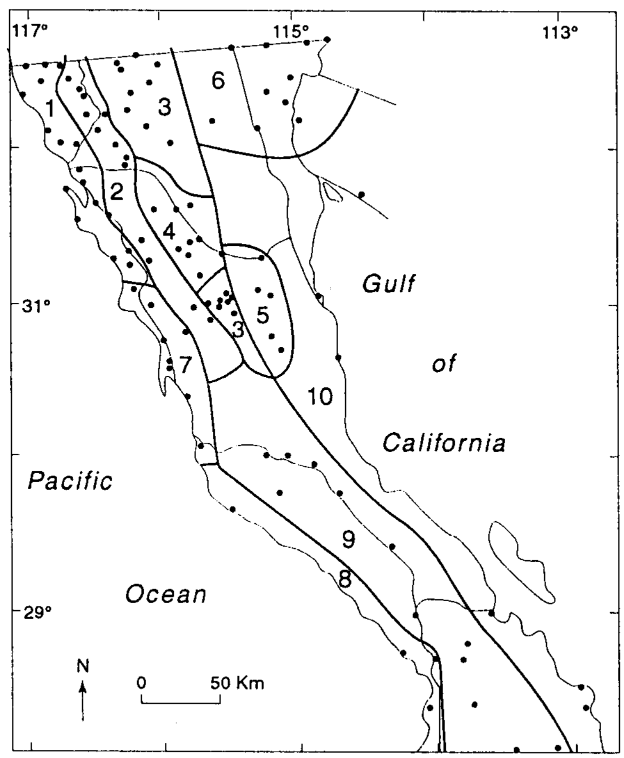


Fig. 2. Location of weather stations and subregions: (1) northern coastal valleys; (2) northern interior valleys; (3) northern Sierra Juárez/Sierra San Pedro Mártir; (4) southern Sierra Juárez/Valle Trinidad; (5) Santa Clara Basin; (6) Mexicali Valley; (7) San Quintín coastal plain; (8) coastal Central Desert; (9) interior Central Desert; and (10) Gulf of California coast.

Because precipitation is a discontinuous variable, amounts were directly averaged only at stations with records longer than 30 years. For short-term stations, mean monthly and annual precipitation were adjusted against the near-neighbor long-term station by statistical normalization methods. Annual departures for short-term stations were estimated by subtracting the annual total of the short-term station from that of the long-term station mean, and dividing this difference by the standard departure of annual totals at the long-term station.

In the sparsely populated mountains, precipitation estimates were subjectively interpolated based on the observation that, during winter frontal storms, prevailing winds are from the southwest at 700 mb (Minnich, 1984). Hence, isohyets were drawn consistent with the observation that

south-and west-facing slopes are zones of maximum orographic lift, and north- and east-facing slopes are zones of maximum descending leeward flow (rain shadows).

For the remote Sierra San Pedro Mártir, supplementary data were obtained from a network of bulk precipitation gauges maintained during 1989-1992 (Minnich *et al.*, 1998), and the snowpack was measured during the winter/spring of 1991 and 1992 by using a standard USDA Soil Conservation Service snow probe.

The variability of annual and monthly precipitation in Baja California and adjacent California due to ENSO was evaluated by comparing annual precipitation departures (July to June) with the Southern Oscillation Index (SOI), which is based on the difference in average surface air pressure at Darwin, Australia and Tahiti in the western Pacific (U. S. Department of Commerce 1999). While El Niño is linked to warm seawater in the east Pacific, the SOI is better linked to the equatorial distribution of surface seawater temperatures (SST's) (Trenberth and Hoar, 1996). The interval classification was used to develop a systematic comparison of precipitation response to SOI.

For the Pacific coast analysis, we evaluate precipitation for 1950-1993 at coastal stations (to minimize effects of orography) along a latitude gradient between Eureka, California (latitude 40°48′) south to Rancho Alegre in central Baja California (latitude 28°17′) with SOI averaged for the precipitation season of each year (November to March). The data were summarized as precipitation means and standard deviations by 0.5 intervals of SOI. The same procedure was applied to monthly data for November to March at San Francisco, Los Angeles, Ensenada, and San Quintín (Las Escobas). To test for uniformity of precipitation departures in the eight subregions of Baja California with ENSO, the SOI was compared with average precipitation departures for long-term stations (established before 1960) in the respective subregions. Because agriculture and ranching activities can benefit from information on the beginning and end of the precipitation season, the monthly precipitation departures with SOI were evaluated for the effect of ENSO on the distribution of precipitation.

4. Results

Average winter precipitation in northern Baja California

Most precipitation is derived from cold fronts because warm frontal discontinuities are minimized, upon the approach of a storm, by adiabatic heating of prefrontal air descending from the Great Basin Plateau and by advection of cool marine air in the cyclone "warm sector" of the California current (Minnich 1984; Minnich 1986). The trade-wind marine layer causes cold fronts to behave like occlusions, resulting in long periods of steady rain. During the prefrontal precipitation period, winds aloft are predominantly southwesterly because frontal zones precede trough axes (Minnich, 1984; Minnich, 1986). Low-level winds are mostly southeasterly from the Pacific ocean. Post-frontal precipitation consists mostly of scattered convective showers concentrated over high terrain, with veering southwesterly to westerly winds aloft. Clouds and precipitation decrease rapidly with the onset of subsidence and advection of dry air following the passage of the trough.

The distribution of winter precipitation in Baja California exhibits several mesoscale trends related to physiography which are not evident in maps from previous studies (Figs. 3-4). North of latitude 31°30′ are two belts of high precipitation, one along the crest of the coastal ranges (maxima, 40 cm), and the other along the Sierra Juárez (maxima, 50 cm). In the Sierra Juárez, orographic lift is dispersed along its gentle western flank, with rain amounts diminished by rain shadows extending from the coastal ranges. The rain shadows also reduce annual amounts to 17-30 cm in the intermediate basins from Valle Ojos Negros to Valle Trinidad. Annual precipitation fluctuates along the west coast, due to orographic lift of storm air masses that may extend upwind as far as 100 km out to sea, as in southern California (Bonner *et al.*, 1971; Pyke, 1972).

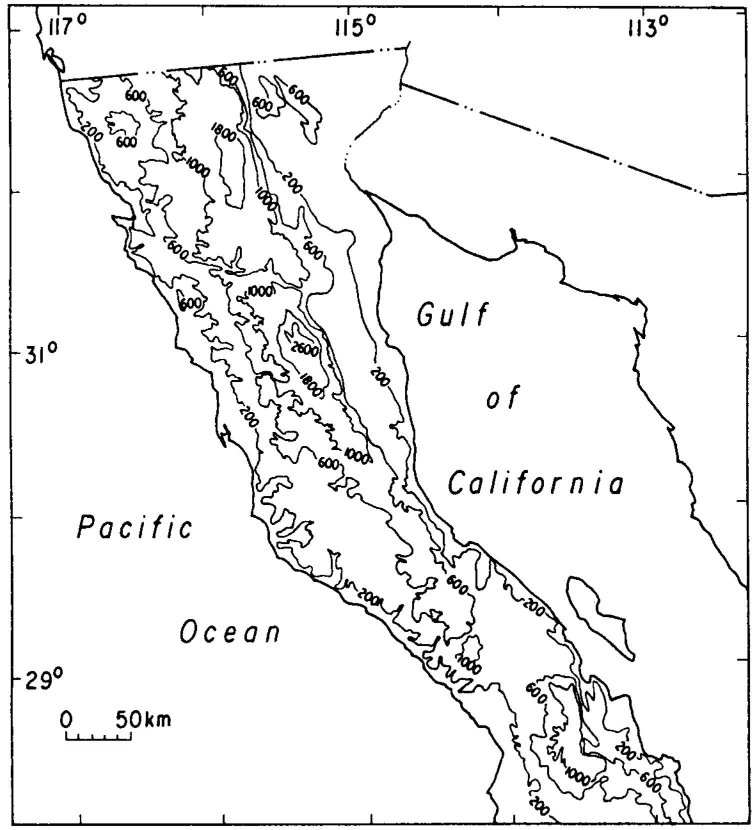


Fig. 3. Topographic map of the State of Baja California. Altitudes are in meters above sea level.

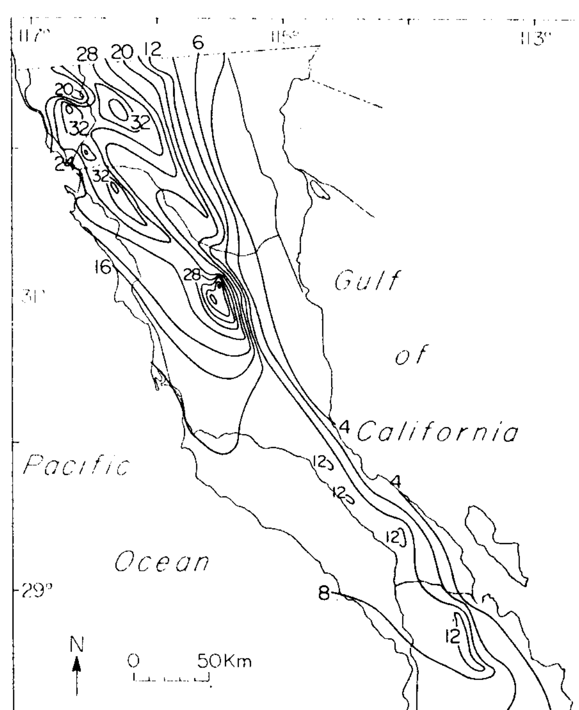


Fig. 4. Average annual precipitation (cm) for November-May.

Precipitation amounts increase southward along the coast from 22 cm near the international boundary to 25-35 cm near Ensenada where the coastal Sierra Juárez, and corresponding zones of orographic lift of rain-bearing winter storms, approach the shoreline. Rain shadows from these coastal ranges extend over the Sierra Juárez proper, and orographic lift of rain-bearing air masses is spread over a wide area along its gentle west-facing slope.

South of Ensenada, coastal precipitation decreases to 15 cm at San Quintín, because the zone of orographic lift shifts inland 60 km at the Sierra San Pedro Mártir. The Sierra San Pedro Mártir has no upwind rain shadows and orographic lift is concentrated along its steep western escarpment. Bulk rain-gauge data for the Sierra San Pedro Mártir thus show annual amounts increasing from 27 cm at Rancho Santa Cruz on the west flank of the range to 50-55 cm on the plateau (Minnich *et al.*, 1998).

Precipitation amounts are mostly 8-12 cm south of latitude 30° where altitudes of 600 to 1000 m result in limited orographic lift of frontal air masses. In central Baja California, relief comparable to that of the northern mountains is limited to isolated high summits, such as those of Sierras San Borja, La Asamblea, and Libertad. Strong rain shadows from the Sierras Ju rez and San Pedro Mártir result in annual amounts of < 6 cm from San Felipe to the Mexicali Valley.

Snowfall in the northern mountains is infrequent below 1,500 m (Fig. 5). The proportion of winter precipitation occurring as snow is estimated at 15% in the Sierra Juárez above 1,700 m (liquid equivalent, 10-15 cm) and > 50% above 2300 m in the Sierra San Pedro Mártir (liquid equivalent, 25 cm). Snowpack measurements showed that water content ranged from 7-12 cm at snow depths of 30 cm in 1991-92, and 34 cm at depths of 90 cm in 1990-91 (Minnich *et al.*, 1998). Snow pack densities were 30-40% between December and March, similar to that reported for California (Miller, 1955). High snow pack densities reflect warm ambient temperatures during winter storms. Snow was entirely melted by April or early May.

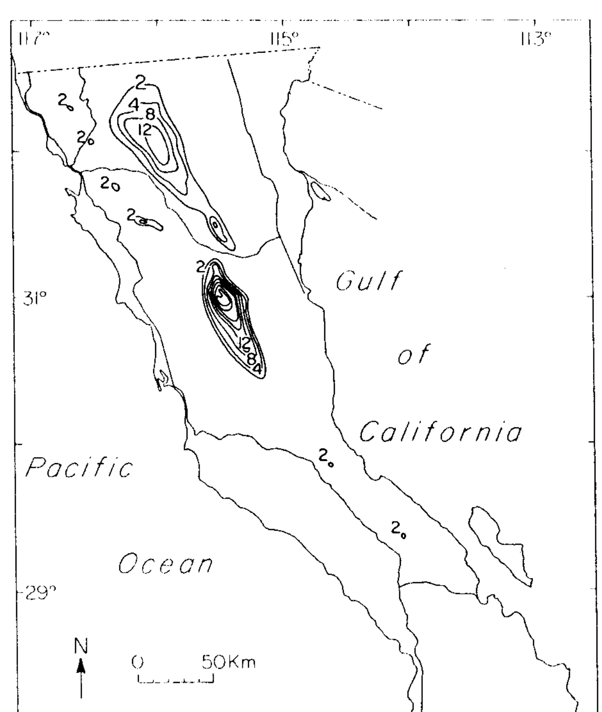


Fig. 5. Mean annual liquid equivalent of snowfall (cm) estimated from methods in Minnich (1986).

Mean Annual Precipitation

The average annual precipitation increases from 25 cm on the coast to 40 cm in the coastal ranges and from 50 cm in the Sierra Juárez to 60 cm in the Sierra San Pedro Mártir, with 20-25 cm in the intervening basins (Fig. 6). Amounts decrease to 8 to 16 cm in the central desert, with < 10 cm along the Gulf coast and < 7 cm in Mexicali Valley. The differences between annual and winter precipitation result from the summer monsoon (July- August) which averages 2-4 cm in the mountains of the Central Desert, 10-20 cm in the Sierras Juárez and San Pedro Mártir, and < 2 cm along the Pacific coast (Minnich *et al.*, 1993). Rare tropical cyclones (September-October) result in average annual precipitation amounts ranging from 1-2 cm along the Pacific coast to 4-6 cm in the mountains, and 2-4 cm along the Gulf of California and Mexicali Valley (Reyes-Coca *et al.*, 1990).

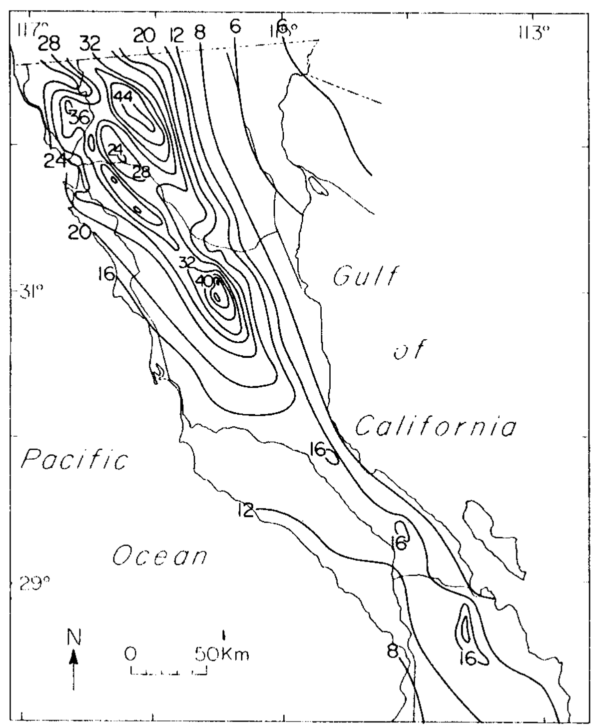


Fig 6. Mean annual precipitation (cm).

The El Niño/Southern Oscillation and precipitation variability

During strong El Niños (SOI < -1.0), annual precipitation departed more than one standard deviation from normal at all stations in southern California and northern Baja California, with the upper bound reaching 270% of normal from San Quintín to Punta Prieta (Fig. 7). Standard deviations in Baja California are sufficiently large that even lower-bound values may approach climatic normals; but north of San Luis Obispo in California, all the lower bounds of standard deviations fall below climatic normals.

Under strong El Niños (SOI <- 1.0), average precipitation departures increased equatorward along the Pacific coast, with maximum values near San Quintín (ca. 200%). Departures decreased to 150% of normal both southward to Rancho Alegre and northward to southern California

(Los Angeles), vanishing in northern California with 115% at San Francisco and 98% at Eureka. Gradients of departure, while consistent with the more ambiguous response of precipitation to ENSO observed in California by Schonher and Nicholson (1989), nonetheless demonstrate that the ENSO signal is unambiguous in northern Baja California.

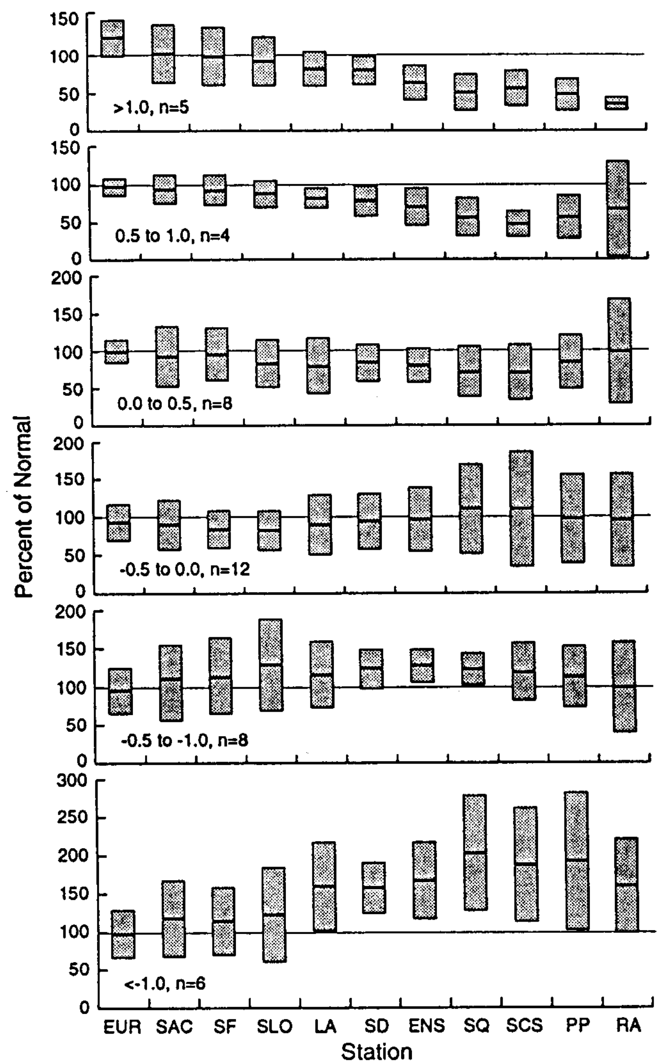


Fig. 7. Precipitation departures, and ± 1 standard deviation of mean annual precipitation compared with the interval classification of the southern oscillation index (SOI); n = number of years in SOI interval. Stations: EUR, Eureka; SAC, Sacramento; SF, San Francisco; SLO, San Luis Obispo, LA, Los Angeles; SD, San Diego; ENS, Ensenada; SQ, San Quintín (Las Escobas); SCS, Santa Catarina Sur; PP, Punta Prieta; and RA, Rancho Alegre.

During weaker El Niños (SOI -0.5 to -1.0), precipitation amounts showed a similar trend of increasing precipitation departures, but values were less extreme. Annual precipitation departures were above normal south of San Francisco, with greatest departures (130% of normal) at Ensenada and San Quintín. Moreover, the lower bounds of standard deviations were also above normal from San Diego to San Quintín. For years with SOI of 0.0 to -0.5, annual precipitation totals were close to normal throughout California and Baja California, with departures within one standard deviation of normal. Precipitation departures tend to be slightly greater in Baja California than in California.

Under moderate and intense La Niña episodes (SOI > 1.0), precipitation departures decreased equatorward along the Pacific coast. Precipitation amounts tended to be above normal in northern California, and normal from San Francisco to San Luis Obispo, with departures within one standard deviation of normal. Annual amounts were below normal south of Los Angeles, but in Baja California even the upper bounds of standard deviations were below normal. Moreover, departures were greater than two standard deviations from normal at both Punta Prieta and Rancho Alegre. Mean annual precipitation was as low as 20% in the Central Desert. During weak La Niña years (SOI 0.0 to 0.5), annual precipitation was also below normal south of San Francisco in both California and Baja California, although the upper bounds of standard deviations were above normal at all stations.

At individual stations, the driest years occurred with different phases of ENSO. The lowest precipitation in Baja California was associated with moderate and strong La Niñas. In southern California, precipitation departures were subnormal in all cold-phase events with SOI >0.0, but in central California (San Francisco, Sacramento) departures were most negative during weak El Niños (SOI 0.0 to - 0.5).

In Baja California and southern California, the variability of precipitation within SOI intervals, as expressed in the range of standard deviations, tends to be largest during El Niño events, reflecting the persistence of drought during cold episodes in these regions. In central California, variability tends to be greatest during strong La Niñas and during both moderate and strong El Niño episodes.

Seasonal distribution of precipitation

Gradients of precipitation departure in Baja California and California, which are linked to SOI, are associated with corresponding shifts in the seasonal distribution of precipitation (Fig. 8). During warm El Niño episodes (SOI <-1.0), the onset of heavy rains typically begins in January, with the highest positive departures occurring in February and March. Precipitation departures, which increase equatorward at all stations, especially south of Los Angeles, decrease again towards southernmost Baja California. Departures are also greater than normal in December in Baja California. At Los Angeles, Ensenada and San Quintín, precipitation means minus one standard deviation still exceed normal precipitation during February and March. Throughout California and Baja California, precipitation is subnormal in November, but in San Francisco it is subnormal in December. Precipitation also exceeds normal from January to March during weak ENSO events (SOI -0.5 to 0.0) from Los Angeles southward, with departures within one standard deviation of the long-term mean.

During strong and moderate La Niña episodes (SOI >1.0, 0.5 to 1.0), average monthly precipitation tends to be greatest in late fall to early winter (November/December) at California stations, with subnormal precipitation after January. In Baja California, precipitation is subnormal during all months, with departures frequently < 50% of normal. At San Francisco and Los Angeles, departures are within one standard deviation of normal during November and December, and the upper bound of standard deviation falls below normal in February and March. But in Ensenada and San Quintín, departures fall more than one standard deviation below normal throughout the rainy season. Interannual variability in monthly precipitation increases equatorward because fewer storms contribute to monthly precipitation totals. During weak La Niña events (SOI 0.0 to 0.5), monthly precipitation is evenly distributed throughout the year, with amounts slightly below normal.

Baja California experiences strong variability in the seasonal distribution of precipitation with ENSO. El Niño years are typically characterized by long precipitation seasons, with recurrent

storms from December through March and sometimes April, even in the Central Desert (e.g. Santa Catarina Sur, Table II). Only one or two major storms may occur during La Niña events, usually in December or January and with little precipitation during most other months, especially south of latitude 30°.

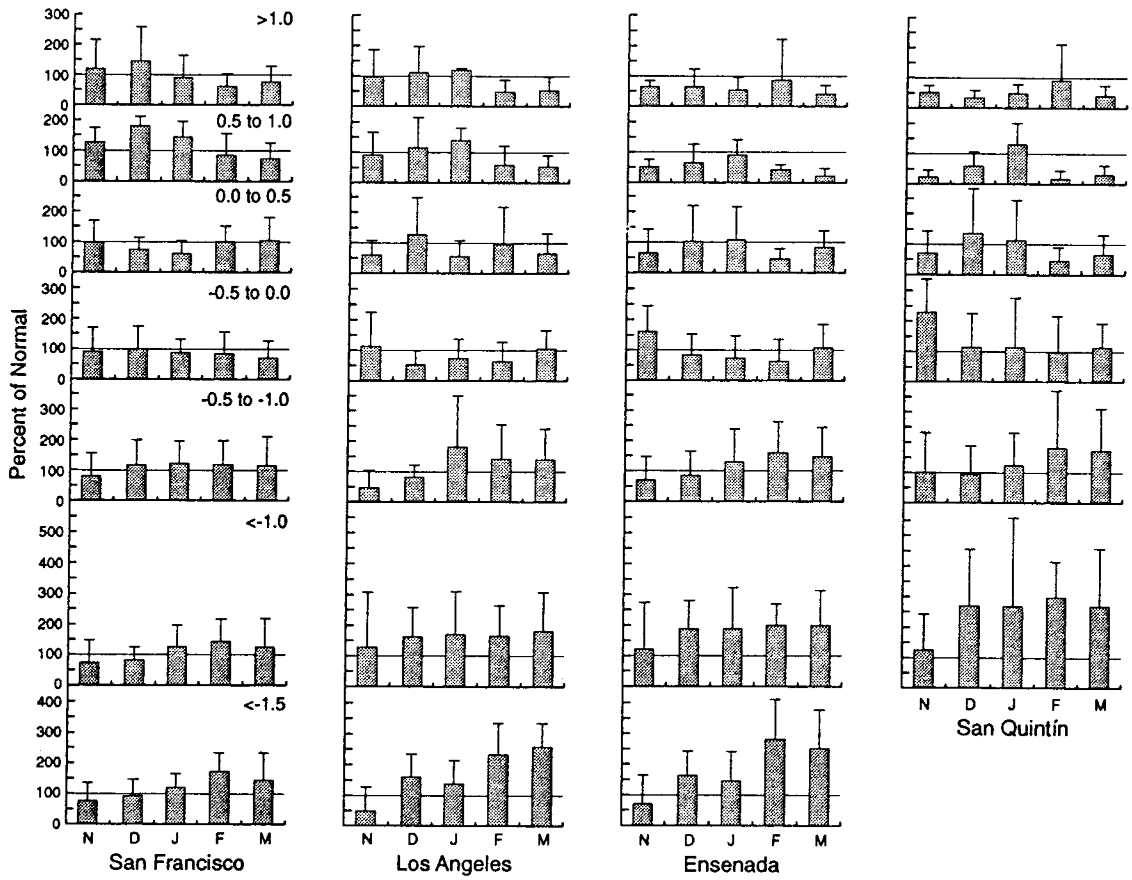


Fig. 8. Monthly precipitation departures, and 1 standard deviation of mean monthly precipitation at San Francisco, Los Angeles, Ensenada and San Quintín compared with the southern oscillation index.

Table II. Monthly precipitation (mm) during selected strong El Niño (SOI < -1.0) and La Niña (SOI > 1.0) at Ensenada and at Santa Catarina Sur.

Ensenada

Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
						El Niño							
1977-78	0	27	0	11	0.7	85	160	148	166	41	0	0	639
1982-83	0	1.5	5	4	85	46	48	104	203	62	0	0	559
1991-92	0	0.2	0	0	23	29	35	99	103	0	1	0	290
						La Niña							
1955-56	0	6	0	0	13	12	37	7	0	23	9.5	0	108
1973-74	0	0	0	0	26	3	61	2	41	4.6	1.5	0	139
1988-89	0	0	0	1	23	35	29	11	34	3.5	0.5	0	136

Santa Catarina Sur

Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
						El Niño							
1977-78	0	20	0	31	0	28	111	93	61	6	2	0	352
1982-83	2	5	9	0	60	56	15	69	85	23	0	0	324
1991-92	0	0	6	35	3	44	39	80	81	15	2	0	305
						La Niña							
1955-56	2	0	0	0	0	1	5	3	0	2	0	0	13
1973-74	0	5	0	0	1.3	26	0	18	3.5	0	0	1	55
1988-89	0.5	0	0	6	2	0	63	0	4	0	0	0	75

Regional precipitation departures in Baja California

Although the year-to-year variation in annual precipitation is poorly correlated with the rank of SOI intervals, gradients in precipitation departures tend to be uniform across Baja California during individual years (Table I). During years with SOI < -1.5 (i.e. 1978, 1983) average precipitation departures in the subregions ranged from 220- 270% of normal. Similarly, years with SOI -0.8 to -0.2 (i.e. 1952, 1979, 1980) produced departures mostly between 120 to 230%. Years with SOI < -1.0 (i.e. 1966, 1987) produced mostly negative departures through most of Baja California. The eight subregions had consistently negative departures during La Niña years. Precipitation reached normal only in the northwestern coastal valleys and mountains during 1975 and 1976.

Precipitation maps for selected years exhibit distributions consistent with the regional precipitation climatology related to physiography, including high-rain zones in the coastal range, Sierra Juárez, and the Sierra San Pedro Mártir, rain shadows eastward from these ranges, and low amounts south of the Sierra San Pedro Mártir due to the absence of topographic relief (Figs. 9a, 9b). Annual totals during the 1977-78 El Niño included 40-100 cm in the northwestern coastal valleys and mountains, 20-35 cm in the Central Desert, and 6-20 cm along the Gulf coast and the Mexicali Valley. During the 1955-56 La Niña, few areas of the northern Sierra Juárez received 20 cm, and annual totals were < 4 cm along the Pacific coast as far north as latitude 31°. The

Central Desert received less < 3 cm and no precipitation fell at Bahía de los Angeles. Bulk rain gauges in the Sierra San Pedro Mártir recorded total winter precipitation of 24-28 cm during the La Niña of 1989-90, and 55-65 cm during the El Niño of 1991-92 (Minnich *et al.*, 1998).

Table I. Precipitation departures in eight subregions[1] of Baja California during warm phase/El Niño years and cold phase/La Niña years (July to June).

Year Ending	'83	'78	'87	'66	'73	'69	'58	'52	'80	'79
Southern Oscillation Index	-3.2	-1.6	-1.6	-1.2	-0.8	-0.8	-0.8	-0.8	-0.6	-0.2
Northern coastal valleys	213	241	85	89	143	113	134	155	191	163
Northern interior valleys	194	223	95	87	101	83	128	162	234	198
Northern mountains	211	223	101	100	110	109	113	158	180	204
San Quintín coastal plain	217	273	64	143	121	89	136	169	193	230
Coastal Central Desert	197	229	75	71	195	69	152	–	137	273
Interior Central Desert	208	226	55	74	161[2]	55	100	–	137	273
Mexicali Valley	239	254	54	72	278[2]	63	131	117	171	201
Gulf of California coast	184	130	24	124	147[2]	49	130	98	75	153

Year ending	'74	'71	'76	'56	'50	'55	'63
SOI (Nov-Apr)	2.2	1.6	1.3	1.2	1.1	0.5	0.4
Northern coastal valleys	63	63	108	45	63	65	49
Northern interior valleys	63	56	118	38	55	54	47
Northern mountains	62	70	95	59	66	53	42
San Quintín coastal plain	45	37	92	21	55	47	60
Coastal Central Desert	35	36	41	44	–	35	118[2]
Interior Central Desert	44	41	60	32	–	47	102[2]
Mexicali Valley	60	41	107	77	22	77	59
Gulf of California coast	25	38	26	19	31	19	168[2]

[1]Stations:

North coast: Tijuana, Presa Rodríguez, Olivares Mexicanos, Ensenada, San Vicente;

Northern interior valleys: Valle las Palmas, Ojos Negros, Santo Tomás, La Providencia, Santa Cruz;

Northern mountains: La Puerta, El Pinal, San Juan de Diós, Santa Catarina Norte, El Alamo, Valle Trinidad;

Mexicali Valley: Presa Morelos, Mexicali, Bataques, San Luís Río Colorado, Delta, Colonia Rodríguez,Rifto, El Mayor;

San Quintín coastal plain: San Telmo, Las Escobas, Santa María del Mar, El Socorro, Colonia Vicente Guerrero;

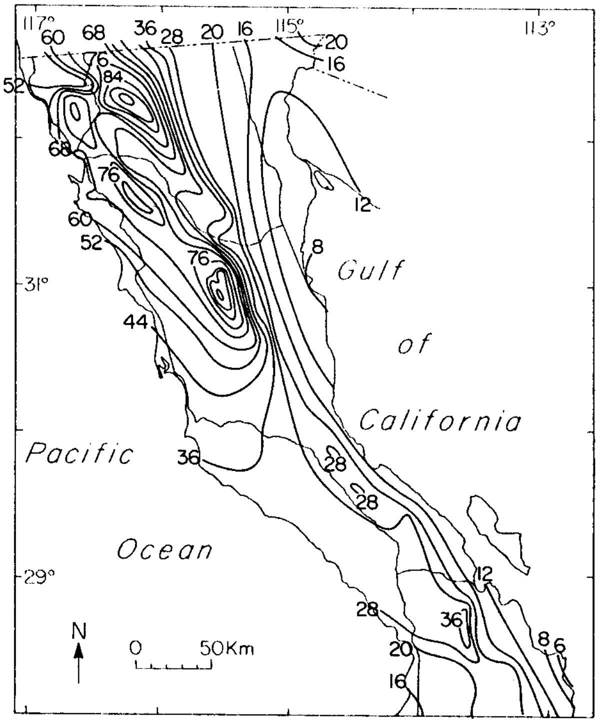
Coastal Central Desert: Rosarito, Rancho Alegre;

Interior Central Desert:: El Progreso, San Agustín, Santa Catarina Sur, San Luís, Chapala, Punta Prieta, San Borja, San Regis, El Arco, Santa Gertrúdis;

Gulf of California coast: San Felipe, Bahía de los Angeles, El Barrfl.

[2]Precipitation amounts increased by tropical cyclones.

A



B

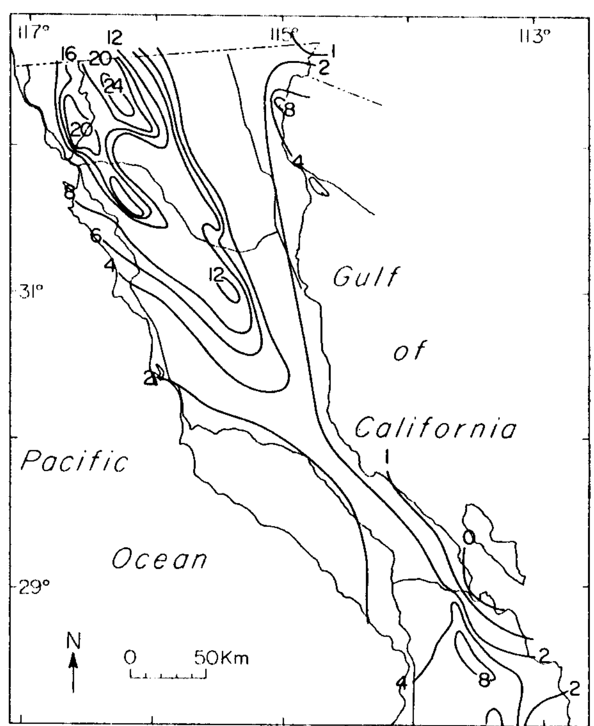


Fig. 9. Annual precipitation (cm) for (A) the El Niño year of 1977-78, and (B) the La Niña year of 1955-56.

5. Discussion

The ENSO has a distinct and consistent precipitation signal in Baja California. However, in comparing the interannual variability (both monthly and annually) with SOI, it should be recognized that large deviations of precipitation from "normal" are inherent in arid regions. Hence, some of the variance is unrelated to teleconnection phenomena.

During years with average rainy season SOI $<$ -0.5, which largely correspond to moderate to strong El Niños (1951-52, 1957-58, 1965- 66, 1968-69, 1972-73, 1977-78, 1982-83, 1991-92) there was above- normal precipitation throughout Baja California. Precipitation departures increased southward from California to Baja California, with maximum departures at 31°N.

Years with SOI $<$ -1.0 had heavier precipitation than years with SOI of -0.5 to -1.0. La Niña events consistently produced subnormal precipitation in Baja California, with departures decreasing southward from California. The severity of drought in Baja California during La Niñas is evidenced by precipitation means greater than one standard deviation below normal.

The interannual variability of precipitation in Baja California is related to the dislocation of the polar-front jet stream along the Pacific coast by ENSO. Theoretical studies indicate that the release of latent heat and divergent outflow (northward flux of angular momentum) from a region of enhanced tropical convection in the central equatorial Pacific Ocean results in the establishment of a train of stationary waves in the polar-front jet stream, and anomalous, highly variable rainfall patterns in many areas of the Pacific basin (Cane, 1983; Rasmussen and Wallace, 1983; Philander, 1990; Lau and Sheu, 1991).

Global circulation composites and general circulation models for El Niño and La Niña events show that circulation anomalies at 500 mb are largely in phase with those at sea level, reflecting the equivalent barotropic structure of the extra-tropical response (Hoerling *et al.*, 1997). During El Niño events, the circulation acquires a positive-phase Pacific-North America pattern (PNA, after Barnston and Livesey, 1987), with a center of action from Hadley convection east of the International Dateline, subnormal heights in the Gulf of Alaska, blocking in British Columbia, and an enhanced Tropical Northern Hemisphere (TNH) teleconnection mode expressed in a southern-branch jet stream across California and the southwestern United States (Renwick and Wallace, 1996; Hoerling *et al.*, 1997).

We interpret the trend for increasing precipitation with decreasing SOI in Baja California to reflect the strength and position of the equatorial warm pool in the eastern Pacific (Fu *et al.*, 1986). The trend for increasing precipitation departures southward along the pacific coast also suggests that the jet stream is dislocated to low-latitude tracks related to the TNH circulation mode. The intensity of El Niño correlates with SOI because SST anomalies shift the position of maximum tropical convection and surface pressure at Tahiti and Darwin (Philander 1990). The large variability in precipitation in Baja California reflects the high interannual variability in the strength of the southern branch.

During La Niña events, the composite circulation acquires a negative-phase PNA pattern, with the center of action in the west Pacific being teleconnected with positive height anomalies in the North Pacific, blocking in the Aleutians, and negative height anomalies over the Pacific Northwest and Canada (Renwick and Wallace, 1996; Hoerling *et al.*, 1997). The jet stream is mostly poleward of Baja California and California, with weak onshore advection of moist surface westerlies onto the west coast of North America.

The increase in annual precipitation in Baja California with decreasing SOI is consistent with findings for California by Schonher and Nicholson (1989), who evaluated California rainfall using the ordinal El Niño classification of Fu *et al.*, (1986). They found that precipitation increases in California with strong warm-phase Type I events, SST anomalies are large and the warmest

equatorial waters are east of 160°W, but the precipitation signal is ambiguous during weaker events, especially in northern California.

Several weak El Niño events, or neutral years associated with high precipitation amounts in Baja California (1978-79, 1979-80; Table I) may relate to a "step-wise" shift toward warm mid-Pacific SST's from 1976 to 1987, a corresponding shift of the Aleutian low to eastern Alaska, and anomalous cold air advection into the central Pacific. These ingredients tended to make El Niño circulations persist for several years after 1976 (Trenberth, 1990). This stepwise shift has been associated with unprecedented long-term warming of the central Pacific beginning in 1976 (Trenberth and Hoar, 1996).

Seasonal precipitation distribution

Precipitation along the Pacific coast during El Niño years tends to be greatest during late winter and spring (February-March), but precipitation during La Niña years tends to be greatest in late fall and early winter (December-January). This is consistent with a trend for increased variability of precipitation during the normally dry spring and fall seasons, and above-normal stream flows in Arizona and the US Southwest (Andrade and Sellers, 1988; Webb and Betancourt, 1992; Cayan and Webb, 1992; Kahya and Dracup, 1994). Seasonal precipitation distributions appear to be related to both local- and global-scale processes.

The enhanced precipitation during El Niños is attributed to unusually warm SST anomalies extending to the west coasts of California and Mexico and greater precipitable water vapor in storm air masses compared to non-El Niño years (Andrade and Sellers, 1988). They attribute the early maximum of winter precipitation in California to correspond with moist storm air masses over Pacific waters that are still warm from the previous summer. During late winter and spring, drought is enhanced by cooling of the California current caused by increased upwelling, which serves to inhibit deep convection (Pyke, 1972). At a global scale, seasonal shifts in precipitation anomalies in Baja California may also be related to geographic shifts in diabatic forcing from the equatorial warm pool and consequent teleconnections into the extra-tropical wave train in the Pacific-North American region (Hoerling *et al.*, 1997). During El Niño episodes, negative height anomalies over the Gulf of Alaska are centered at 135° W in December, but then retrogress to 150° W by spring. This corresponds with a discontinuous westward shift in the zone of deep tropical convection (SST's > 28°C) away from the warm pool southwest of Mexico in fall, to a position east of the International Dateline by spring. This shift is related to a seasonal reduction in cold water advection of the Peruvian current equatorial cold tongue during the Antarctic summer.

We hypothesize that the extra-tropical wave-train tends to retrogress, and the flow of the TNH southern branch is most intense from California and eastward during early winter, and from the central Pacific into California by late winter-early spring. The intensification of early winter storms in the US Southwest, combined with warm SST's off Baja California and Mexico during early winter, may account for above-normal precipitation south of Ensenada in December. Low-latitude frontal storms moving into Baja California from the Pacific contribute to heavy precipitation in late winter and spring.

During La Niñas, the wave train shifts progressively eastward with time (Hoerling *et al.*, 1997), and the center of deep convection moves from north of New Guinea (140°E) in fall to west of New Guinea (and south of the equator) by spring. According to Hoerling *et al.* (1997), there is a corresponding progressive shift in negative 500 mb departures from 130°W near the US Pacific Northwest in December to 100°W in Canada by March. This shift is frequently associated with the development of a strong negative-phase PNA pattern in January, which

is dominated by a Hudson Bay vortex-east coast trough, with a strong ridge over the North American west coast. We hypothesize that the potential for frontal disturbances reaching Baja California is correspondingly greatest in early winter, but few disturbances reach Baja California during strong La Niña years. Spring months are mostly dry (Fig. 8) because SST's in the eastern equatorial Pacific are below the 28°C threshold for deep tropical convection and TNH flow.

Uniformity of interannual precipitation departures in Baja California

The similarity in annual precipitation departures across the eight subregions of Baja California (Table I) suggests that, during El Niños, frontal storms cumulatively produce uniform precipitation patterns across the State. During frontal storms, the majority of precipitation occurs in association with southerly, cool moist and stable low-level air flows over the upwelling Pacific current. Post-frontal convection is usually concentrated over the mountains and accounts for small precipitation amounts due to drying and subsidence of the air mass (Elliott 1958; Elliot and Hovind, 1964). Because vertical velocities in fronts are often low, the distribution of precipitation strongly reflects the physiographic lift of storm air masses. In northern Baja California, precipitation amounts are greatest on the western slopes of the near-coastal ranges, and the Sierras Juárez and San Pedro Mártir. South of latitude 30°, precipitation decreases rapidly because this parallel marks the southern limit of the continuous high mountains of the Peninsular Ranges (> 1,500 m) and thus of significant orographic lift of frontal air masses. Moist storm air masses circulate eastward across the peninsula, with little orographic lift or precipitation occurring until they reach Arizona or the Sierra Madre Occidental of northwestern Mexico. During El Niño years, precipitation rates are high even in the plains of the Sonoran Desert despite the strong rain shadows of the Peninsular Ranges. A contributing factor may be the high incidence of cut-off lows in the southwestern US (Cayan and Webb, 1992), which generate strong south-to-southeasterly low-level advection of moist flow into that region from the Gulf of California. Easterly flow results in unusual orographic lift on the eastern escarpment of the Peninsular Ranges.

Snowfall accumulations play a small role in regional hydrology. Winter snowpacks are substantial only in the highest plateaus of the Sierra San Pedro Mártir because climatological snowlines average 2300 m (Minnich, 1986). In addition, snowlines occur at higher elevations as annual precipitation increases. This is related to higher storm snowlines, which are associated with low-latitude cyclones that are in turn linked to TNH circulations during El Niño years. It follows that low snowline years are associated with light precipitation amounts over large areas of the Peninsular Ranges, while during wet years, heavy snows are restricted to the highest summits of the Sierra San Pedro Mártir. As a consequence, runoff during the spring snowmelt is low and storm runoff is not reduced by mountain snowfall, in a manner similar to southern California (Kahrl *et al.*, 1978).

Implications for land use and natural resources

The ENSO perturbs weather patterns in many countries of the Pacific Basin, including Mexico, and frequently disrupts agricultural and marine economic activities tied to normal climate and seasonal rhythms. Because the large heat capacity of ocean water results in relatively long durations of ENSO, however, basic monitoring of ocean temperatures permits prediction at time-scales of months. Recent advances in the prediction of ENSO events may lengthen the time span of weather prognoses. Several countries including Peru, Brazil, Australia, and Indonesia, have used ENSO forecasts to maximize agricultural yields (Battisti and Sarachik, 1995). The effects of ENSO on agricultural production are also being modeled in Mexico, and preliminary results are being used to help in decision making (Tiscareño Lopez *et al.*, 1998)

In Baja California, the interannual variability of annual and monthly precipitation is strongly linked to ENSO events. El Niño events tend to result in heavy precipitation, while drought is almost certain during La Niña events. Precipitation is concentrated in late winter/early spring during low SOI years (El Niños) and during late fall/early winter during high SOI years (La Niñas).

The opening of the Transpeninsular Highway, and of Highway 3 from Ensenada to San Felipe, during the 1970's has contributed to the rapid growth of agriculture and grazing in the northern Peninsula. With timely, long-range precipitation forecasts, the region's history of alternating drought and floods can be mitigated. Aquifers could be recharged, and fluctuations in the available water supply could be reduced, by developing a system of flood-control retention dams and percolation basins. This would be especially important for urban centers that depend upon scarce water resources imported either from the nearly exhausted Colorado River or from scanty nearby surface and groundwater basins.

Rainfed agriculture and grazing operations would benefit if farmers and ranchers could be provided with predictions, on the scale of several months, regarding the reliability of moisture and especially the timing and intensity of drought. Farmers and ranchers should also be aware that, counter-intuitively, the onset of rainy seasons is delayed during high-rainfall years associated with El Niños, but rains arrive early in dry years associated with La Niñas. Hence, planting decisions should not be based on early-season precipitation patterns, but rather on long-term precipitation correlations related to ENSO.

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